III.C.3 A Low-Cost Soft-Switched DC/DC Converter for Solid Oxide Fuel Cells

Objectives

- Develop a low-cost DC-DC converter for low- to high-voltage power conversion as the standard interface between the SOFC source and the load-side DC-AC inverter.
- Develop a low-cost 5 kW DC-AC inverter with a minimum energy efficiency of 99% operating with >400 VDC input.
- Develop power management control strategies and demonstrate the ability to supply and consume reactive power while simultaneously supplying active power to the utility grid.
- Develop sensory and control logic to enable autonomous/semi-autonomous response to aid supporting grid voltage and frequency needs without nuisance tripping or disconnection of the fuel cell system.

Accomplishments

- Demonstrated a new soft-switching DC-AC inverter with efficiency of 99% at 425 V input voltage and 5 kW output power condition. With inclusion of filter components, the overall efficiency achieves 98% at full load.
- Demonstrated the low input voltage SOFC power conditioning system with a system-level efficiency of 94% at full-load.
- Developed a universal power conditioning system that allows standalone load and grid-tie using digital phase-lock loop technique.

Jason Lai (Primary Contact), Sung Yeul Park, Seungryul Moon, Jian Liang Chen, and Junhong Zhang
Virginia Polytechnic Institute and State University
614 Whittemore Hall
Blacksburg, VA 24061-0111
Phone: (540) 231-4741; Fax: (540) 231-3362
E-mail: laijs@vt.edu

DOE Project Manager: Don Collins
Phone: (304) 285-4156
E-mail: Donald.Collins@netl.doe.gov

Subcontractors:
Southern California Edison, Los Angeles, California

Introduction

The Virginia Tech SECA project has been focusing on high-efficiency low-cost power conversion for the solid oxide fuel cell (SOFC) power conditioning systems. In our Phase I effort, an interleaved soft-switching DC-DC converter has been successfully developed and demonstrated 97% peak efficiency. The focus of this past year was to develop a highly efficient DC-AC inverter as the subsequent stage. Our design target for the DC-AC inverter is to reach near perfect conversion of 99% efficiency. This inverter can be connected through an inductor-capacitor (LC) filter to the standalone household AC loads or a large inductor to the utility grid interconnection.

The DC-DC converter and DC-AC inverter are integrated as the complete power conditioning system (PCS) for SECA SOFC testing to verify the efficiency and to show power flow control capability between fuel cell and utility grid. Through a number of iterations and design optimization, our inverter has successfully demonstrated the 99% efficiency target. Together with the early developed, highly efficient DC-DC converter and an output stage filter, which consumes 1% power, the entire PCS has reached 94% efficiency at the 5 kW full-load condition. For the same input voltage and output power, our SECA Industrial Team partner, Siemens-Westinghouse, reported only 80% efficiency with the PCS purchased from their supplier. A recently developed 48 V input voltage, 1 kW output power state-of-the-art PCS only achieved 88.5% efficiency [1]. With the superior efficiency achieved by the proposed all soft-switching PCS, the significance to the SECA program and SOFC design is a substantial savings on power loss that allows the fuel cell manufacturer to reduce the size of the fuel cell stack and the reduction of fuel consumption.

Approach

Major loss components of the state-of-the-art DC-AC inverter are device conduction and switching losses. The only way to reduce conduction loss is to add as much silicon as possible. However, the device that has been widely used in DC-AC inverters is the insulated gate bipolar transistor (IGBT), which has a fixed junction voltage drop that can never disappear. Our approach is to replace the IGBT with power MOSFET, which is a pure resistive loss device, so its conduction loss can be reduced to less than 1% given sufficient silicon area. However, the power MOSFET has a body diode, which generates a large reverse recovery loss when it is turned off. Thus, the power MOSFET has never been used in high-voltage high-power DC-AC inverters. To solve the power MOSFET switching loss problem, the proposed approach is to use the advanced soft-switching technique to eliminate the switching loss associated with the MOSFET body diode reverse recovery.

Figure 1 shows the proposed soft-switching inverter circuit. The power MOSFET switches S_1, S_2, S_3, and S_4 are the main switching devices, and the small IGBT switches S_{x1}, S_{x2}, S_{x3}, and S_{x4} are the auxiliary switches. Small resonant inductors L_{ra} and L_{rb} resonate with the capacitors across the main switching devices to produce zero voltage before the switch is turned on, thus avoiding diode reverse recovery loss. The soft-switching principle and control design methodology are described in detail in references [2] and [3].

A circuit diagram of the PCS power stage and control design of the PCS for utility grid-tie are shown in Figure 2. For a standalone PCS, the output only needs to be filtered by inductor L_{o1} and capacitor L_{o2}. For the grid-tie inverter, an additional inductor L_{o2} is needed to reduce the output current ripple content. A circuit breaker (CB) is also needed to connect and disconnect the PCS. A digital signal processor (DSP) based controller has been developed for the power flow control. We designed a phase lock loop (PLL) to obtain the grid synchronization signal and to produce the in-phase or orthogonal sine waves. These sine waves are multiplied with the real power command P_{ref} and reactive power command Q_{ref} to obtain the reference control current i_{ref}. A proportional-integral (PI) controller H_i(s) is designed to obtain the duty cycle signal $d(t)$ and to produce the desired pulse-width-modulation (PWM) signals for the DC-AC inverter switches.

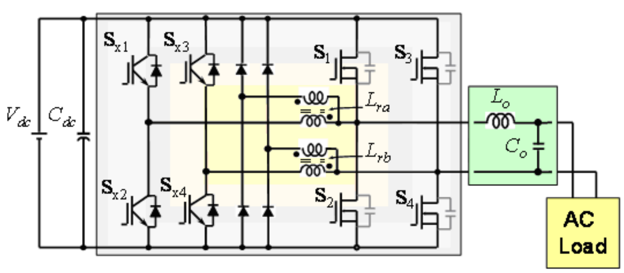

FIGURE 1. Circuit Diagram of the Proposed Soft-Switching Inverter

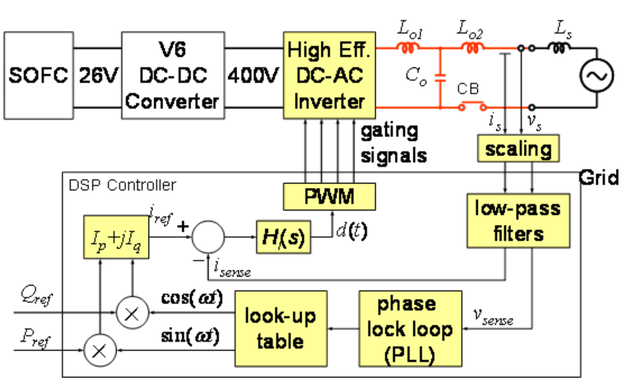

FIGURE 2. Control System of a Grid-Tie SOFC Power Conditioning System

Results

Using the commercially available devices and components, our initial soft-switching inverter design achieved 97.5% efficiency at 5 kW, which was better than most state-of-the-art inverters, but not enough to meet our efficiency goal. We then contacted the power MOSFET manufacturer to solicit a donation of high voltage, high power MOSFET dies for the development of a new soft-switching device module. We received the donation of 100 dies from Infineon and worked with Advance Power Technology to package the phase-leg module to eliminate the parasitic component associated losses. Our second version achieved the design target of 99% efficiency. Under the full-load 5 kW condition, the device steady-state temperature rise is around 20°C with only natural convection heat sinking. Such a "cool" operating condition can ensure long-term reliability of the PCS.

The newly developed soft switching inverter has been integrated with the high-efficiency DC-DC converter for the PCS system-level test. Figure 3 shows the circuit diagram and photograph of the entire PCS efficiency measurement. The fuel cell source voltage V_{fc} is obtained from the SOFC simulator, which consists of a power supply and a source resistance. To ensure accurate reading, a current viewing shunt resistor is connected in between the SOFC simulator and the PCS prototype. The total source resistance including SOFC internal resistance and shunt resistance is

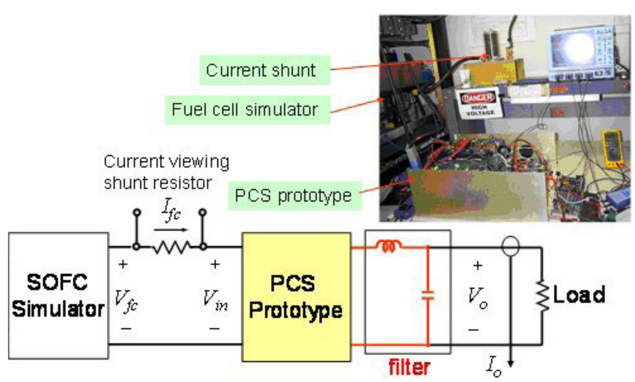

FIGURE 3. The PCS Efficiency Measurement Circuit Diagram and Photograph of Test Setup

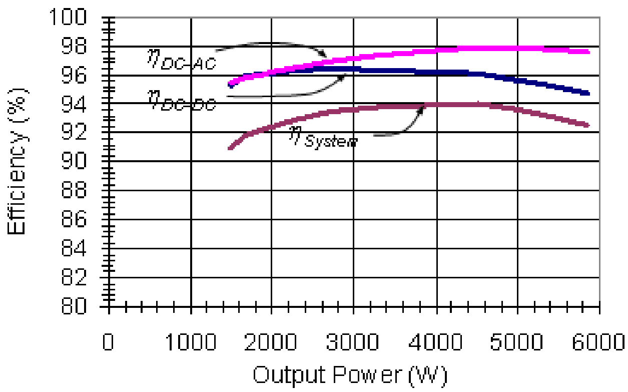

FIGURE 4. The Soft-Switched PCS Efficiency Profiles under the SOFC Simulator Test

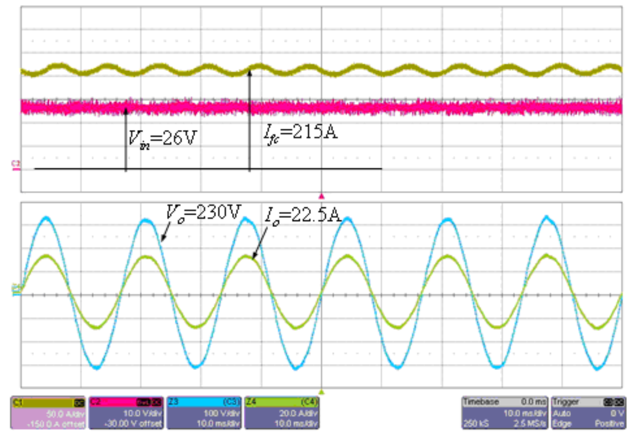

FIGURE 5. The Soft-Switched PCS Input and Output Voltage and Current Waveforms at Full Load

22.423 mΩ. The output of the PCS is connected to a resistive load bank through an LC filter. The load bank sits underneath the bench. The simulator, current shunt, and the PCS hardware prototype along with the measurement instrumentation are shown in the photograph.

The system-level efficiency profiles with SOFC simulator as the source are shown in Figure 4. The no-load simulator output voltage in this case is 32 V. With the total source resistance of 22.423 mΩ, the converter input voltage at 6 kW drops to about 25 V. This new PCS is the only reported all soft switching PCS in the world. The soft switching is not only applied to the DC-DC converter, but also the DC-AC inverter. The DC-AC inverter efficiency η_{DC-AC} including output filter stage peaks at 98% at near full-load condition. This implies that without the output stage LC filter, the power stage DC-AC inverter efficiency peaks at 99%. The DC-DC converter efficiency η_{DC-DC} peaks at 97% at about half load. The overall system efficiency η_{System} peaks at 94% in the load range from 70% to 90%. The test has been extended to 6 kW, or 20% overload without forced-air cooling. The temperature rise of the heat sink is less than 20°C at the full-load condition. It can be foreseen that the unit will be very reliable in long-term operation.

Figure 5 shows measured PCS input and output voltage and current waveforms at the full-load condition. The input voltage V_{in} contains a high-frequency switching ripple, and the input current I_{fc} contains a 120 Hz low-frequency ripple, which can be reduced by the active ripple cancellation technique. The soft-switching inverter was originally designed for better efficiency, but a better waveform quality was also achieved, as indicated in the lower traces of output voltage V_o and current I_o waveform. The major reason for the high-quality sinusoidal waveform is substantial reduction of electromagnetic interference (EMI) emission with the proposed soft-switching technique.

Conclusions and Future Directions

A highly efficient soft-switching DC-AC inverter has been successfully developed. The inverter achieves a near perfect power conversion efficiency of 99%. Together with the previously developed highly efficient DC-DC converter and an output LC filter, the entire power conditioning system has been integrated as the first reported all soft-switching PCS in the world. The unit has been tested using an SOFC simulator as the source. The output stage can be connected to a standalone load as well as the utility grid through an additional inductor and a circuit breaker. Our next step is to test the unit with a Siemens-Westinghouse SOFC under grid-tie condition. The system will include real and reactive power flow control. New sensory and control strategies will incorporate the input from the utility partner – Southern California Edison. Major anticipated accomplishments through future work are listed as follows.

- Develop power management control strategies and demonstrate the ability to supply and consume reactive power while simultaneously supplying active power to the utility grid.
- Develop sensory and control logic to enable autonomous/semi-autonomous response to aid supporting grid voltage and frequency needs without nuisance tripping or disconnection of the fuel cell system.
- Test the entire PCS at EPRI-Solutions to show the performance of EMI and power quality under grid-tie control conditions.

Special Recognitions & Awards/Patents Issued

1. A U.S. patent entitled Multiphase Soft Switched DC/DC Converter and Active Control Technique for Fuel Cell Ripple Current Elimination was filed in November 2005. The patent was originally filed as U.S. Provisional Application Ser. No. 60/654,332 in February 2005.

2. The pending patent has been licensed to PEMDA Corp., Knoxville, Tennessee.

FY 2006 Publications/Presentations

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2. Junhong Zhang and Jih-Sheng Lai, "A Synchronous Rectification Featured Soft-Switching Inverter Using CoolMOS," *Proceedings of IEEE APEC*, March 2006, pp. 810–815.

3. C. Liu, A. Johnson, Jih-Sheng Lai, "A novel three-phase high-power soft-switched DC/DC converter for low-voltage fuel cell applications," *IEEE Transactions on Industry Applications*, December 2005, pp. 1691–1697.

4. Jih-Sheng Lai, Changrong Liu, and Donald Collins, "Active Control Technique for Fuel Cell Ripple Current Elimination," Poster presentation at 2005 Fuel Cell Seminar, Palm Spring, CA, November 2005.

5. Jih-Sheng Lai, "A high-performance V6 converter for fuel cell power conditioning system," *Proc. of IEEE Conference on Vehicle Power and Propulsion*, September 2005, pp. 624-630.

6. Ken Stanton and Jih-Sheng Lai, "A Temperature Dependent Fuel Cell Model for Power Electronics Design," *Proc. of IEEE PESC*, Recife, Brazil, June 2005, pp. 1647-1651.

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1. D.G. Holmes et. al., "An Innovative, Efficient Current-Fed Push-Pull Grid Connectable Inverter for Distributed Generation Systems," *Proceedings of IEEE PESC*, Jeju, Korea, June 2006, pp. 1054–1060.

2. J.-S. Lai and J. Zhang, "Efficiency Design Considerations for a Wide-Range Operated High-Power Soft-Switching Inverter," *Proceedings of IEEE Industrial Electronics Conference*, Raleigh, NC, Nov. 2005, pp. 604-609.

3. Junhong Zhang and Jih-Sheng Lai, "A Synchronous Rectification Featured Soft-Switching Inverter Using CoolMOS," *Proceedings of IEEE APEC*, Dallas, TX, March 2006, pp. 810–815.